System-Wide Optimization
of the NAS

Matt Jardin

Banavar Sridhar

Automation Concepts Research Branch

NASA Ames Research Center

**VAMS Technical Interchange Meeting #3**

14-15 January, 2003.

Outline

1. **Problem Scope & Objectives**
2. **Core Ideas**
3. **High-Level System Concept**
4. **Core Idea Descriptions**

- Sequential Optimization
- Neighboring Optimal Wind Routing (NOWR)
- Conflict Grid (Conflict Detection)
- Conflict Resolution (Perturbation NOWR)

5. **Analysis & Simulation Results**
6. **Scenario Development**
7. **Roadmap**
8. **Conclusion**

Problem Scope:
Class A Airspace Over U.S.
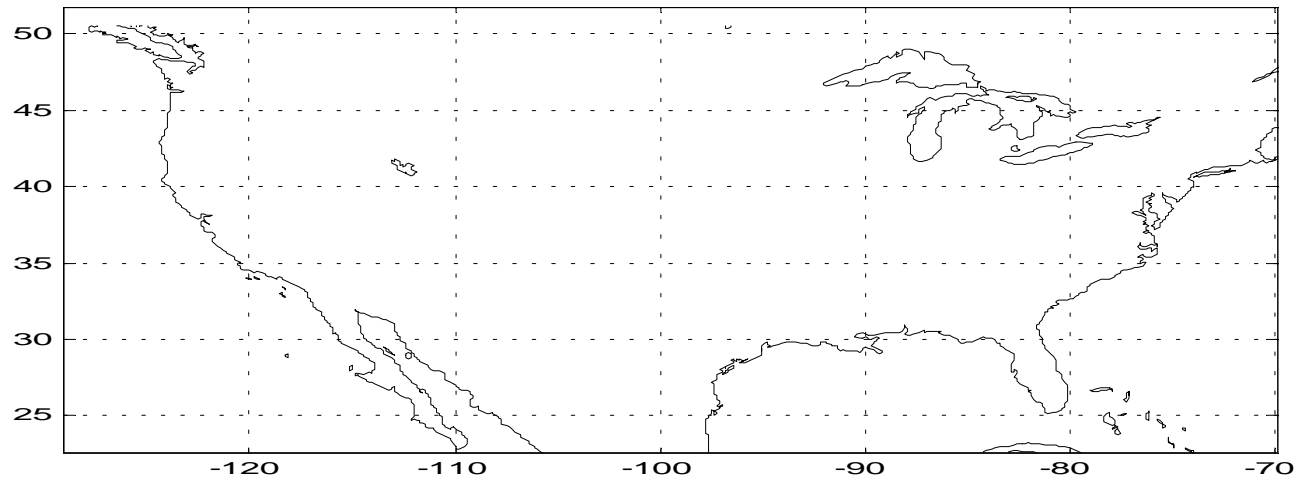
- Area: .... 3 million nmi^2
- Daily Flight Ops above 18000 feet: 38,000
- Peak Traffic Load: ....3000 Aircraft
- Peak Load at Busiest Flight Level:...........................500 Aircraft
- Unique Airports Supporting High-Altitude Traffic:................200

Objective

Develop a Practical Real-Time Method to Optimize and Deconflict Enroute Trajectories of All Aircraft on a Continental Scale
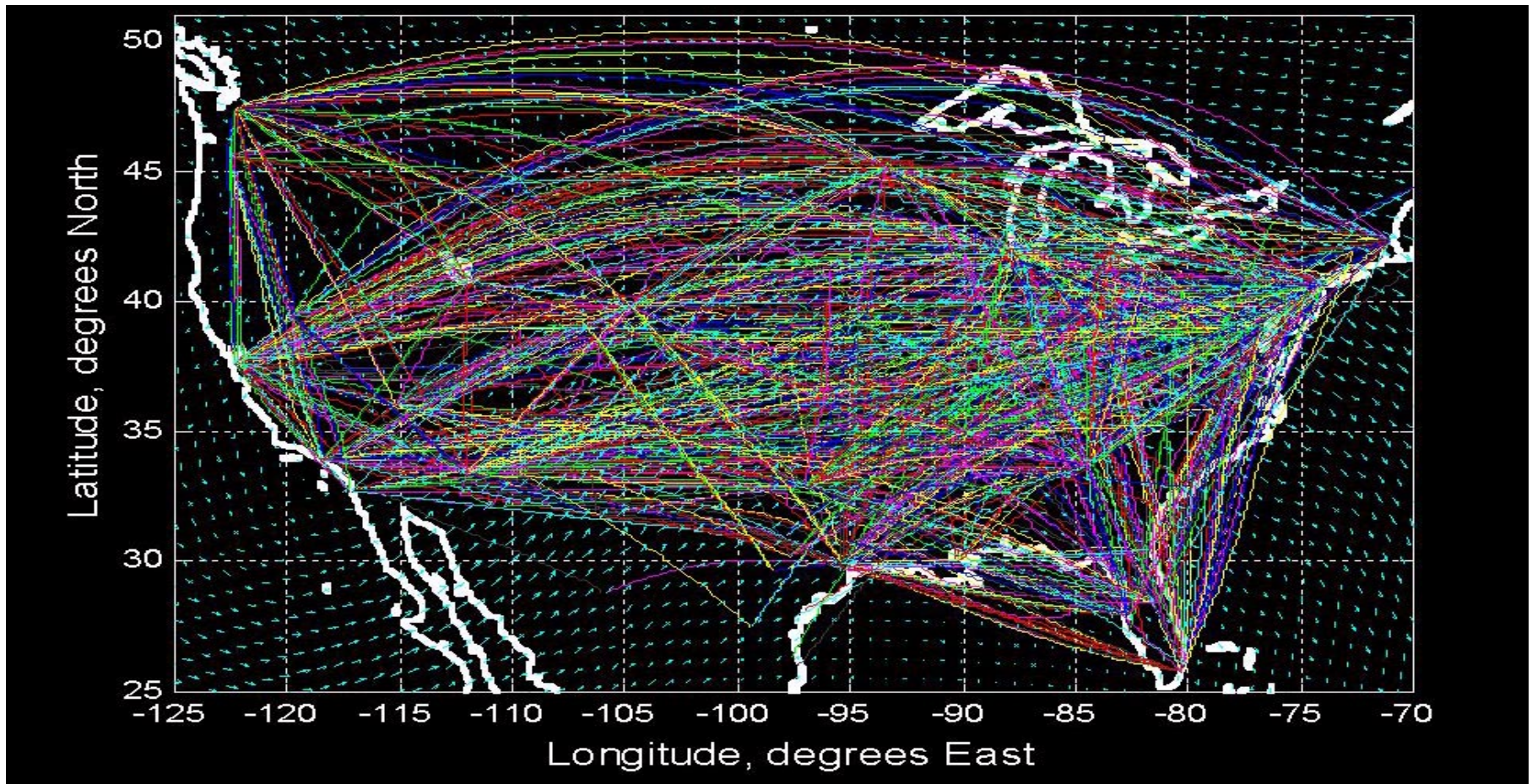
Quantitative Goals

- Reduce Direct Operating Costs by 4.5%

- Save Over 500 Hours of Flight Time Each Day

- Achieve Potential Savings of Nearly $1 Million per Day ($360 Million/Year)

- Increase Capacity while Maintaining Safety

Core Ideas:

Sequential Trajectory Optimization & Conflict Resolution

- Reduce NP-hard Problem to a Polynomial-Time Problem
- Achieve Measurable Near-Optimum Solutions

Neighboring Optimal Wind Routing (NOWR)

- Free Flight Routes are Wind Optimal, *NOT GREAT CIRCLE!*
- Computational Primitive: Algorithm Must be *FAST!*
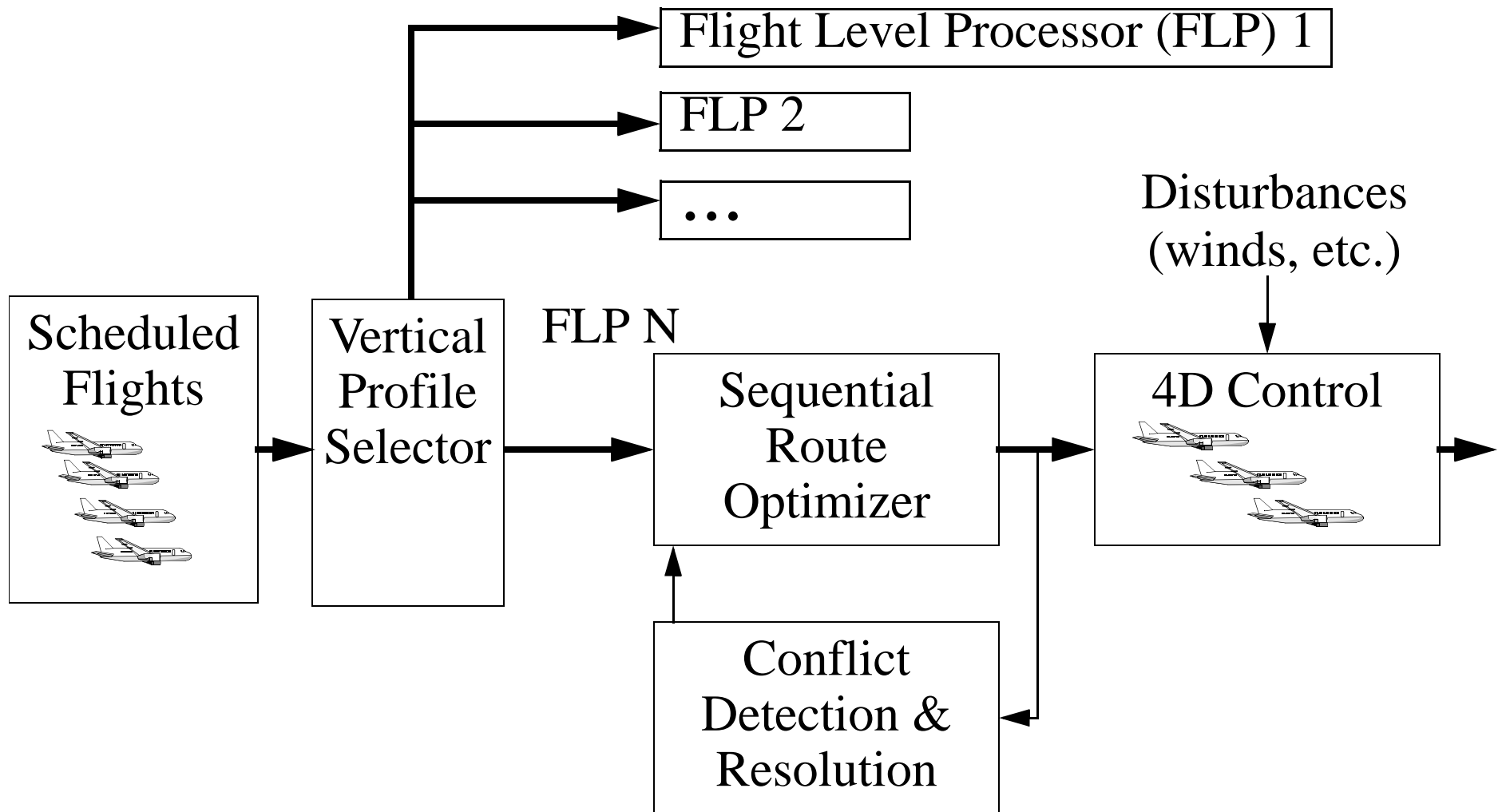- NOWR Easily Adapted for Conflict Resolution

Conflict Grid for Conflict Detection

- Virtually Computationally Free Conflict Detection
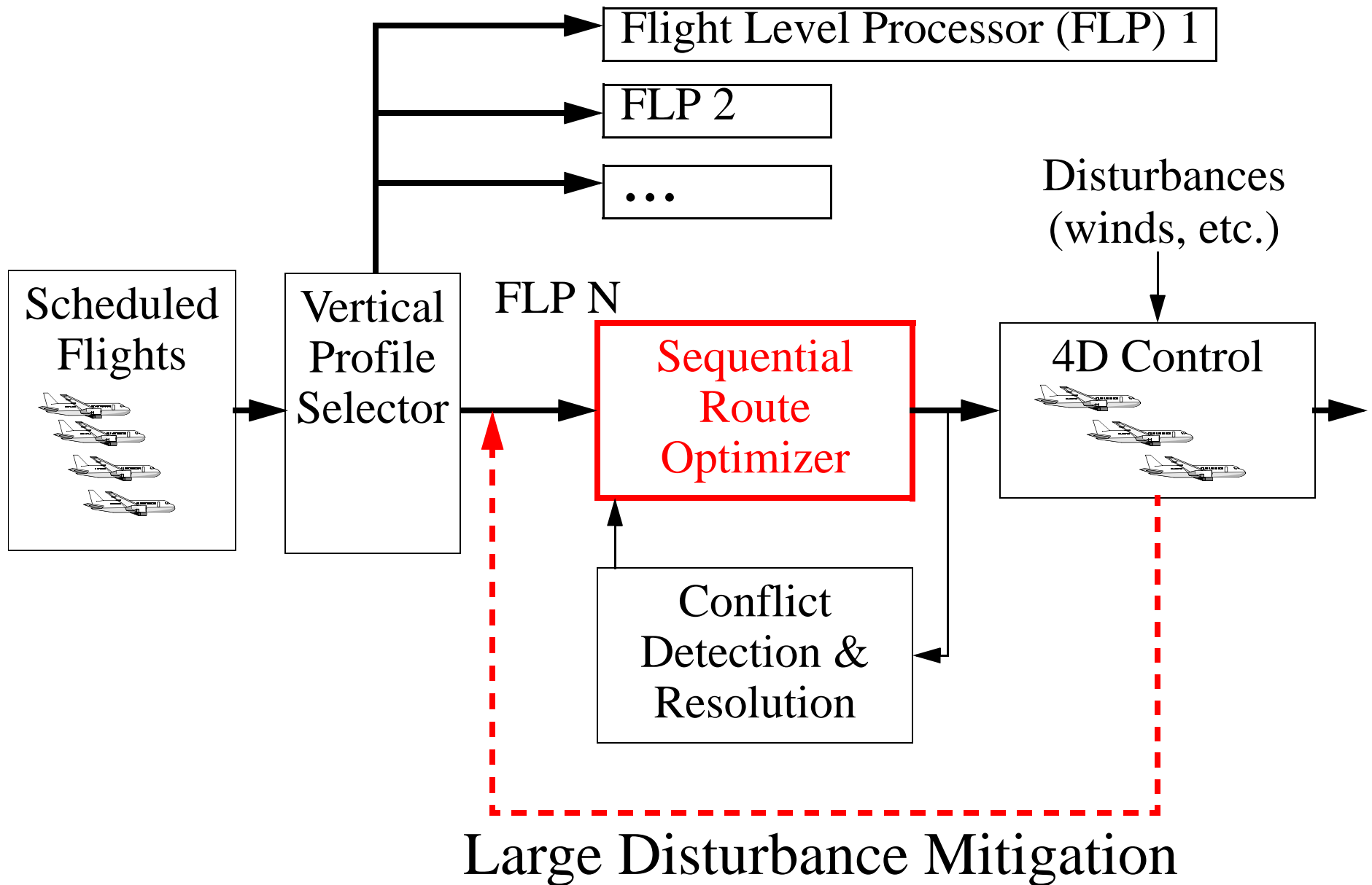- Generalized Conflicts (other aircraft, Weather Cells, SUA, etc.)

Enhanced 4-Dimensional (4D) Flight Plans

- Rigorous 4-D Trajectory-Based Approach to ATC
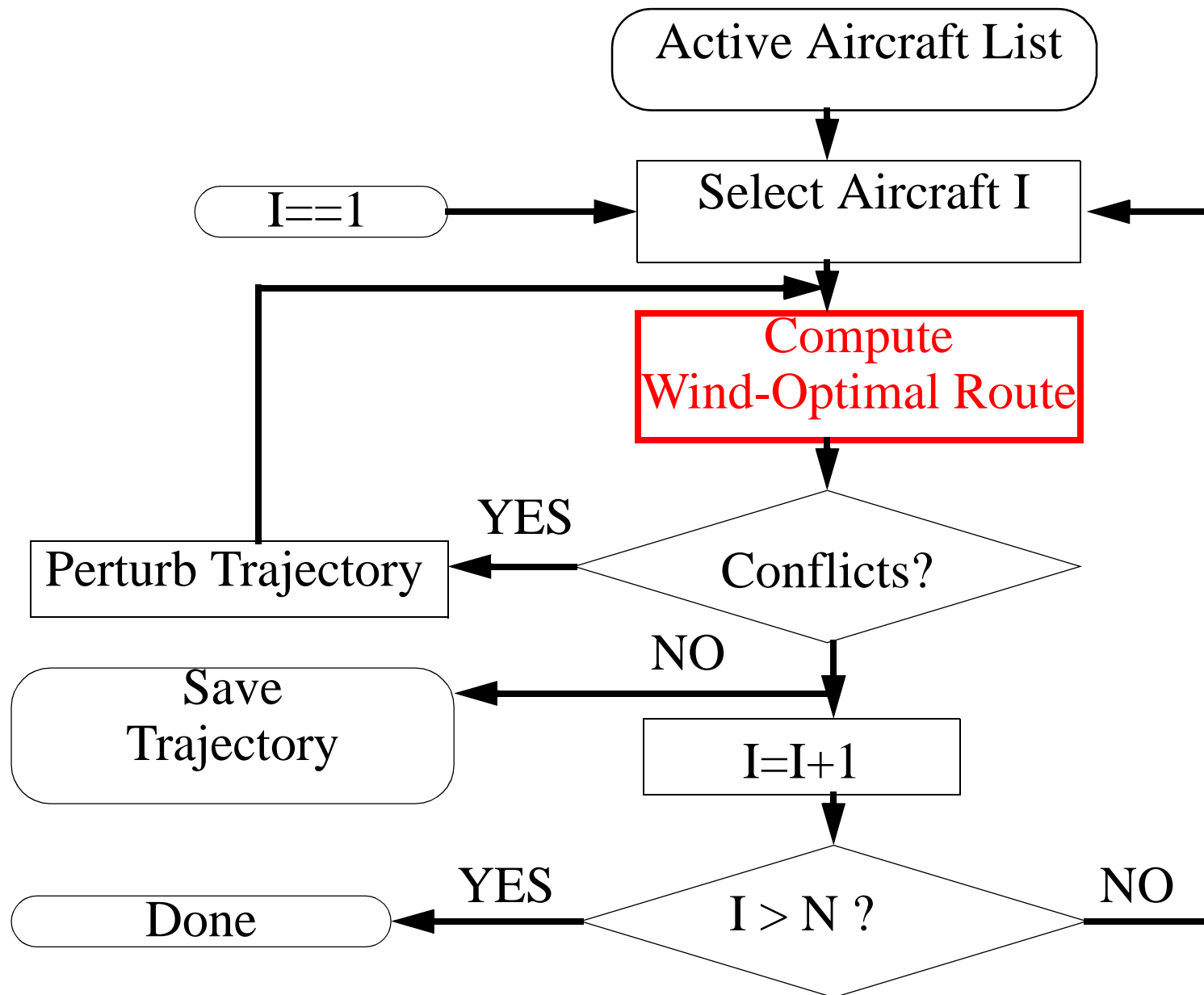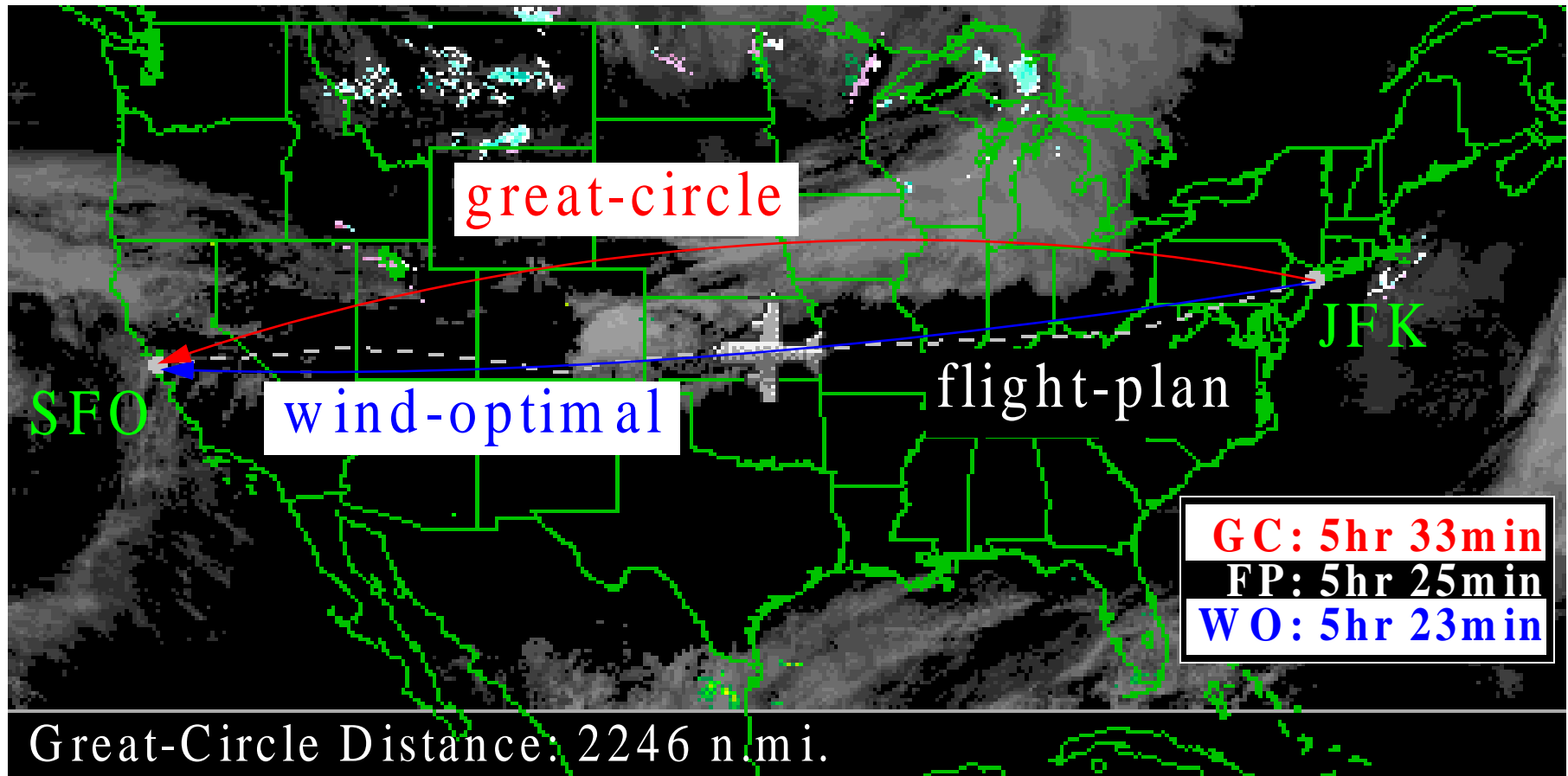
High-Level System Concept

Flight Level Processor (FLP) 1

FLP 2

...

Disturbances
(winds, etc.)

Scheduled
Flights

Vertical
Profile
Selector

FLP N

Sequential
Route
Optimizer

4D Control

Conflict
Detection &
Resolution

High-Level System Concept

Flight Level Processor (FLP) 1

FLP 2

...

Disturbances
(winds, etc.)

Scheduled
Flights

Vertical
Profile
Selector

FLP N

Sequential
Route
Optimizer

4D Control

Conflict
Detection &
Resolution

Large Disturbance Mitigation

Sequential Optimization

Active Aircraft List

Select Aircraft I

I==1

Compute
Wind-Optimal Route

Conflicts?

YES

Perturb Trajectory

NO

Save
Trajectory

I=I+1

I > N ?

YES

Done

NO

Wind Optimal Routing

great-circle

wind-optimal

flight-plan

SFO

JFK

GC: 5hr 33min
FP: 5hr 25min
WO: 5hr 23min

Great-Circle Distance: 2246 n.mi.

FLIGHT: UNITED AIRLINES 15 (B744)
DEPARTING: KENNEDY
ARRIVING: SAN FRANCISCO
DEPARTURE TIME 12:22 P.M. PST
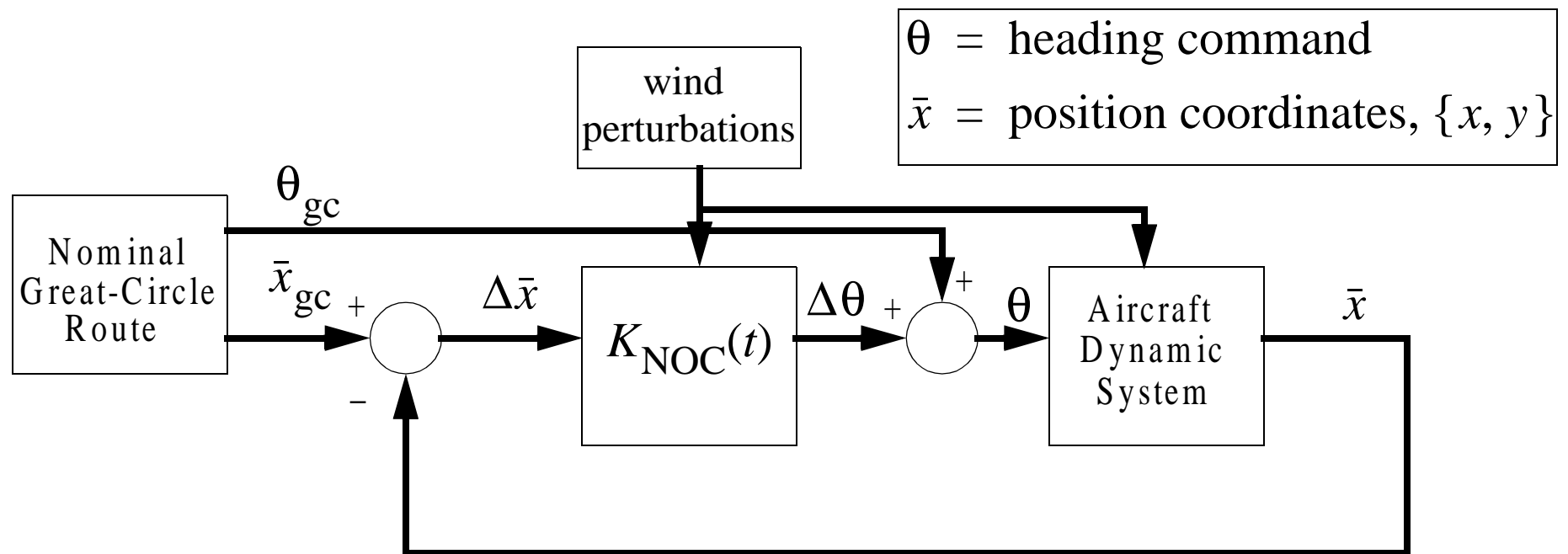EXPECTED TO ARRIVE IN 2 HRS 46 MIN (5:47 P.M. PST)
SPEED: 441 Knots, ALTITUDE: 39000 Feet

Flight-plan image courtesy of:
http://www.flightprogress.com/

Roll the Film!

Neighboring Optimal Wind Routing

- Feed forward nominal great-circle heading commands
- Feedback perturbations in the winds and aircraft position
- Compute NOC gains: $K_{\text{NOC}}(t) = -H_{uu}^{-1}[(H_{ux} + f_u^T(\bar{S} - \bar{R}\bar{Q}^{-1}\bar{R}^T))]$

θ = heading command

$\bar{x}$ = position coordinates, $\{x, y\}$

wind perturbations

θ_{gc}

Nominal Great-Circle Route

$\bar{x}_{\text{gc}}$ +

$\Delta\bar{x}$

$K_{\text{NOC}}(t)$

$\Delta\theta$ +

θ

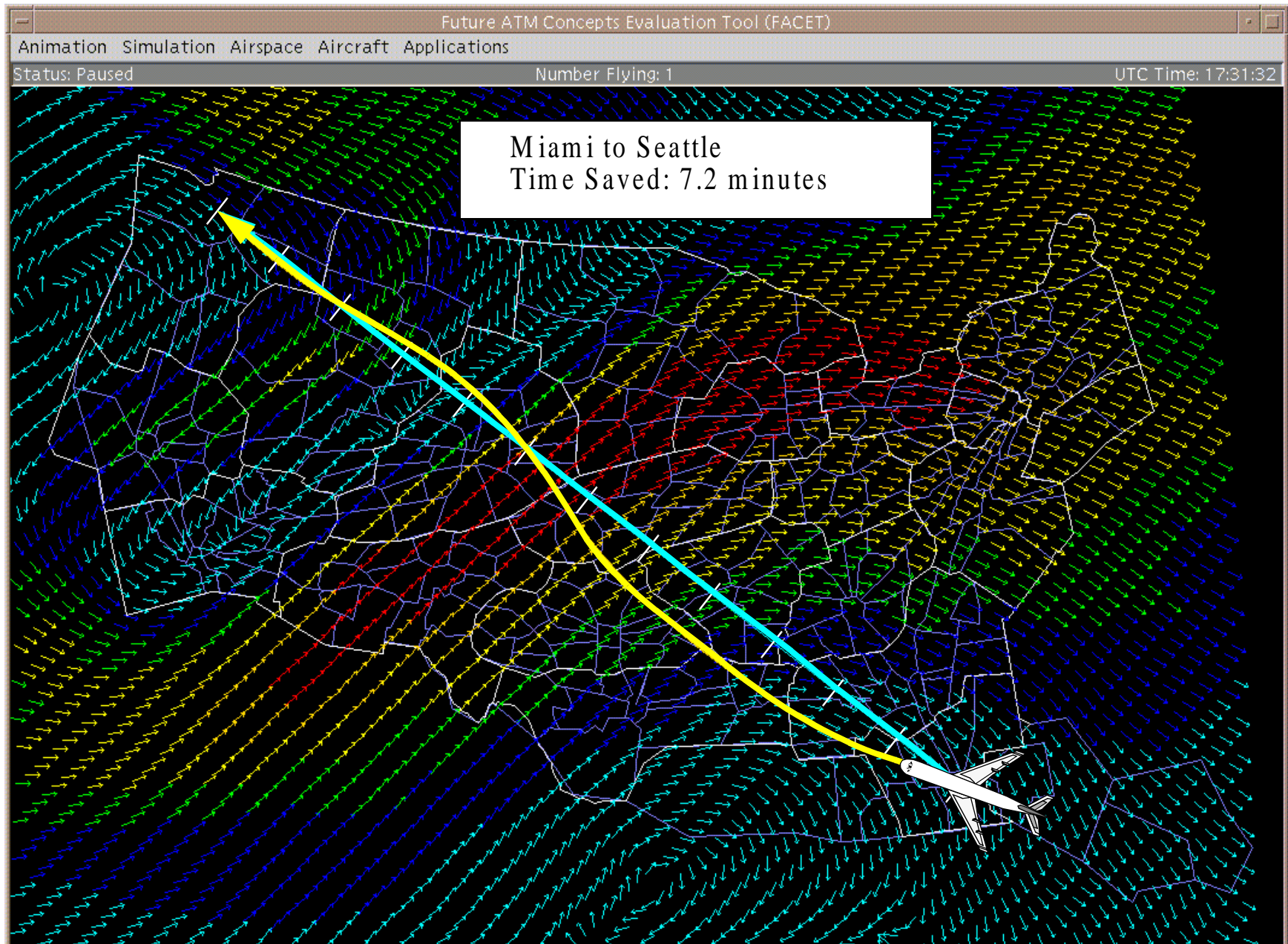Aircraft Dynamic System

$\bar{x}$

−

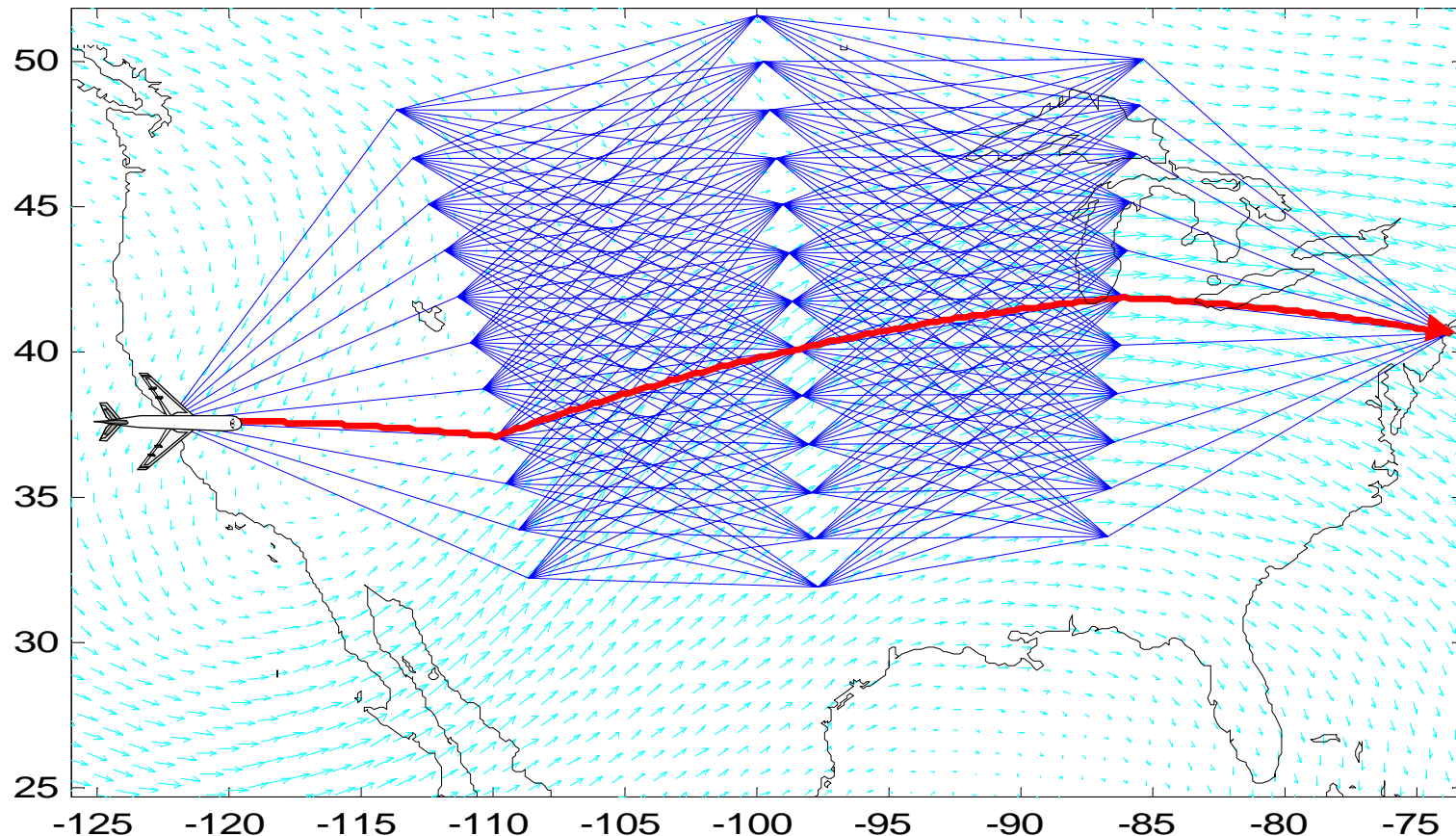- See Journal of Guidance, Control, & Dynamics, Vol. 24, No. 4.

NOWR Example
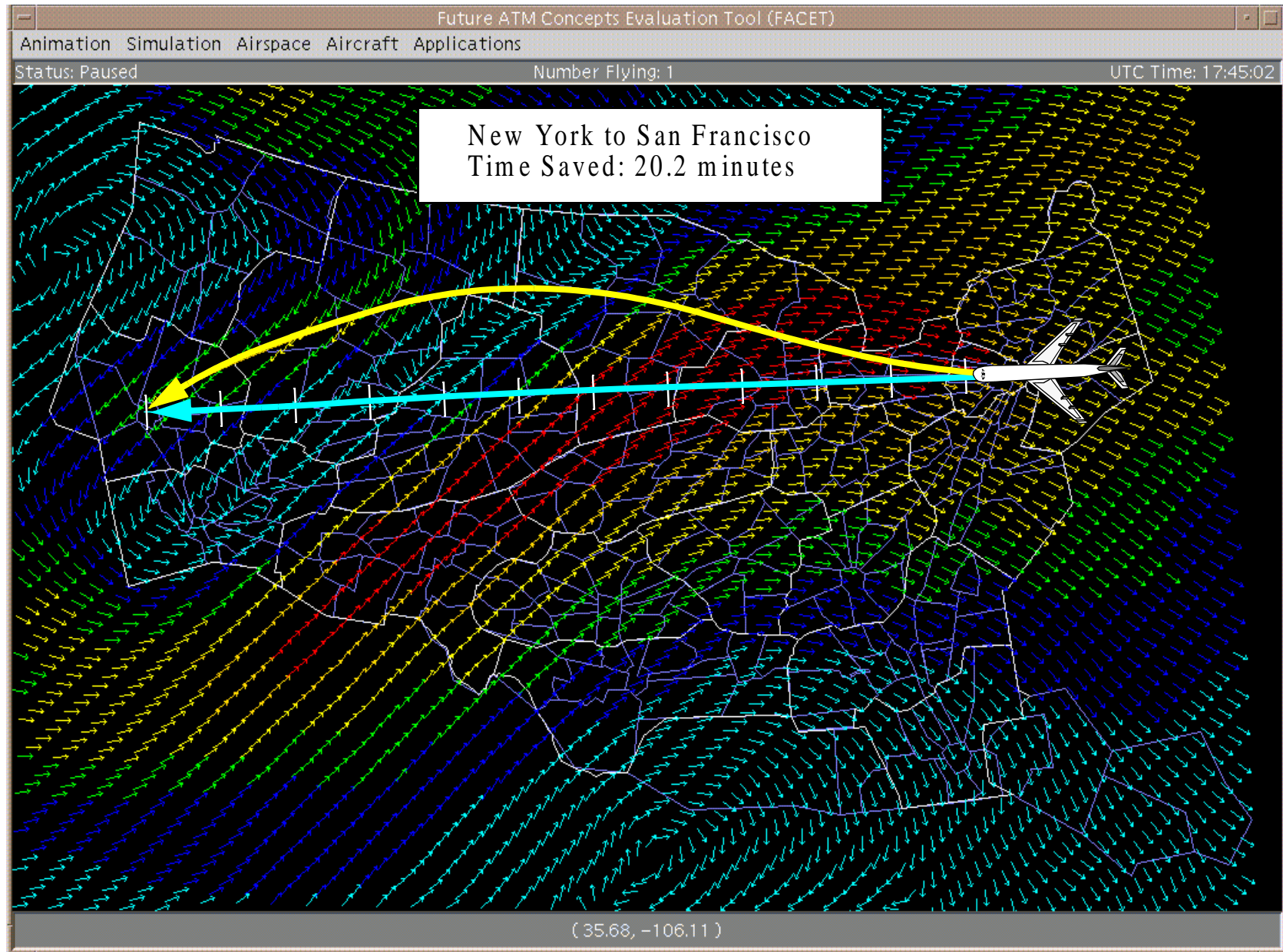
NOWR Example #2

Dynamic Programming

- Search a Discrete Grid for Minimum-Time Route
- Apply Simplifications to Reduce Computation Time
- Trade-off Between Computation Speed and Optimization Performance

NOWR Performance

Dynamic Programming Solution Comparisons

- Directed Graph Search for Optimal Trajectories

- Varying Grid Resolutions

- 6 Different Real Wind Conditions

- 42 Different Cross-Country Flight Routes

- Compute Average Floating-Point Operations (FLOPs)

- Compute Average Total Flight Time Across All Simulations
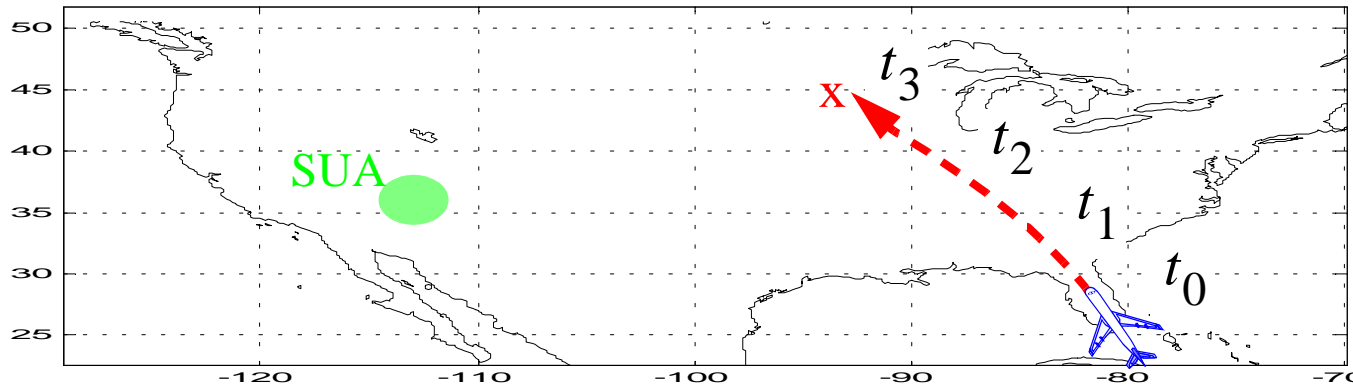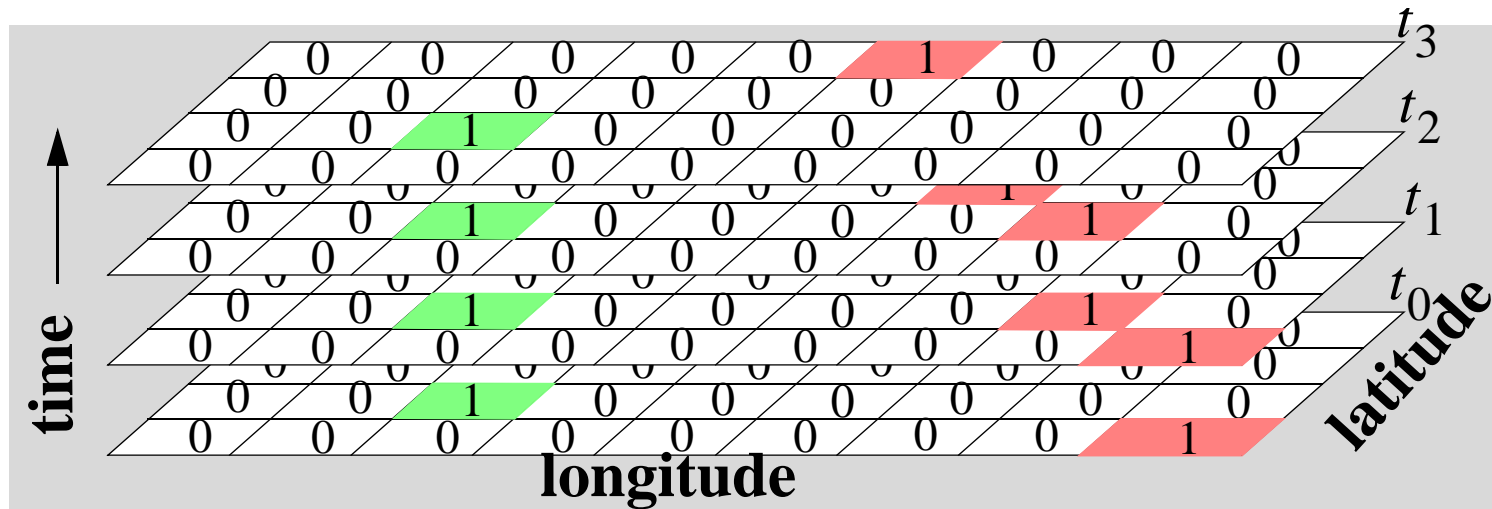
Results

- 40 milliseconds per NOWR computation (450 MHz Sun Ultra)

- NOWR solution within 0.25% of Optimum on Average

- Fastest DP solution took 5 times longer than NOWR

- DP solutions very coarse
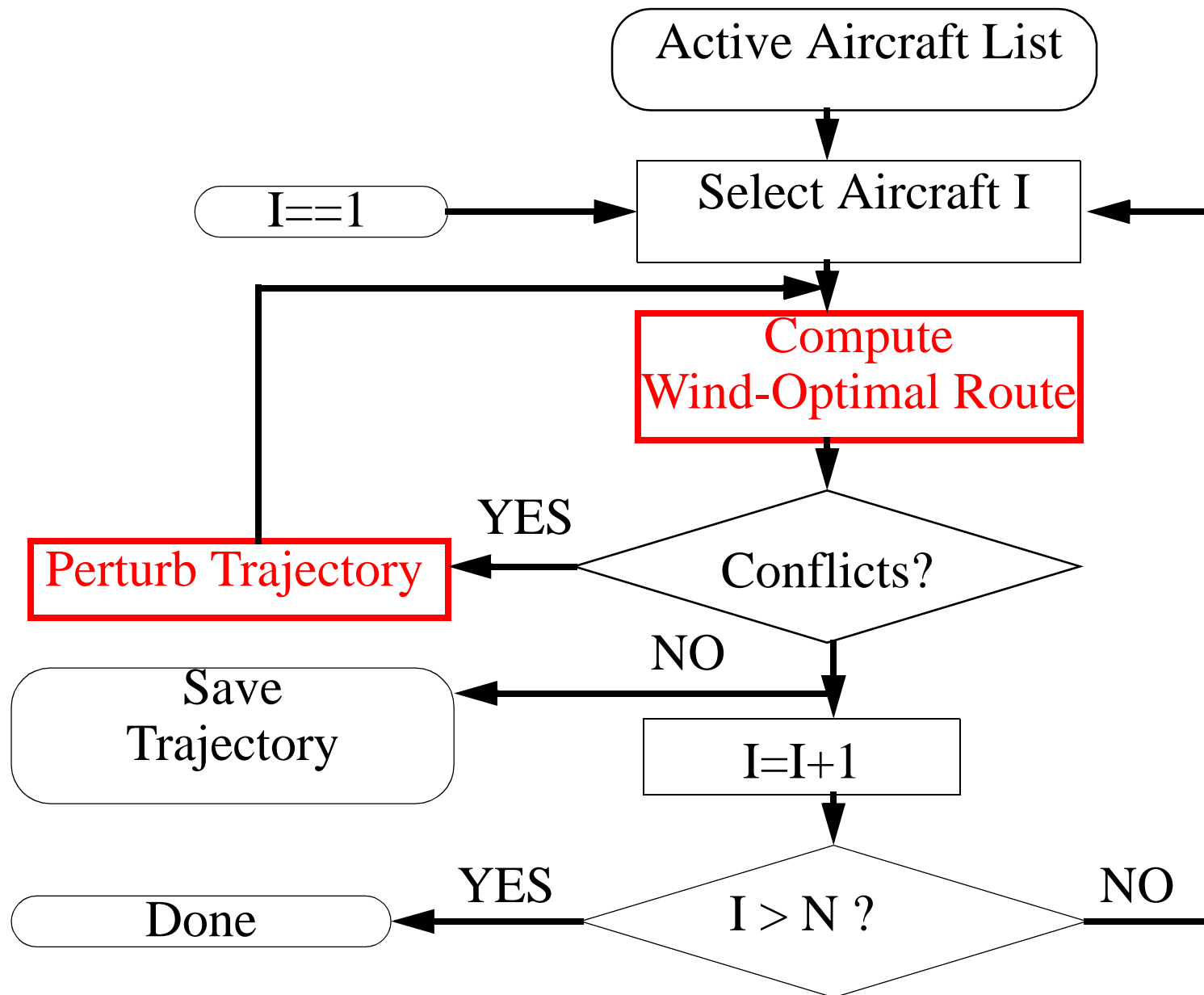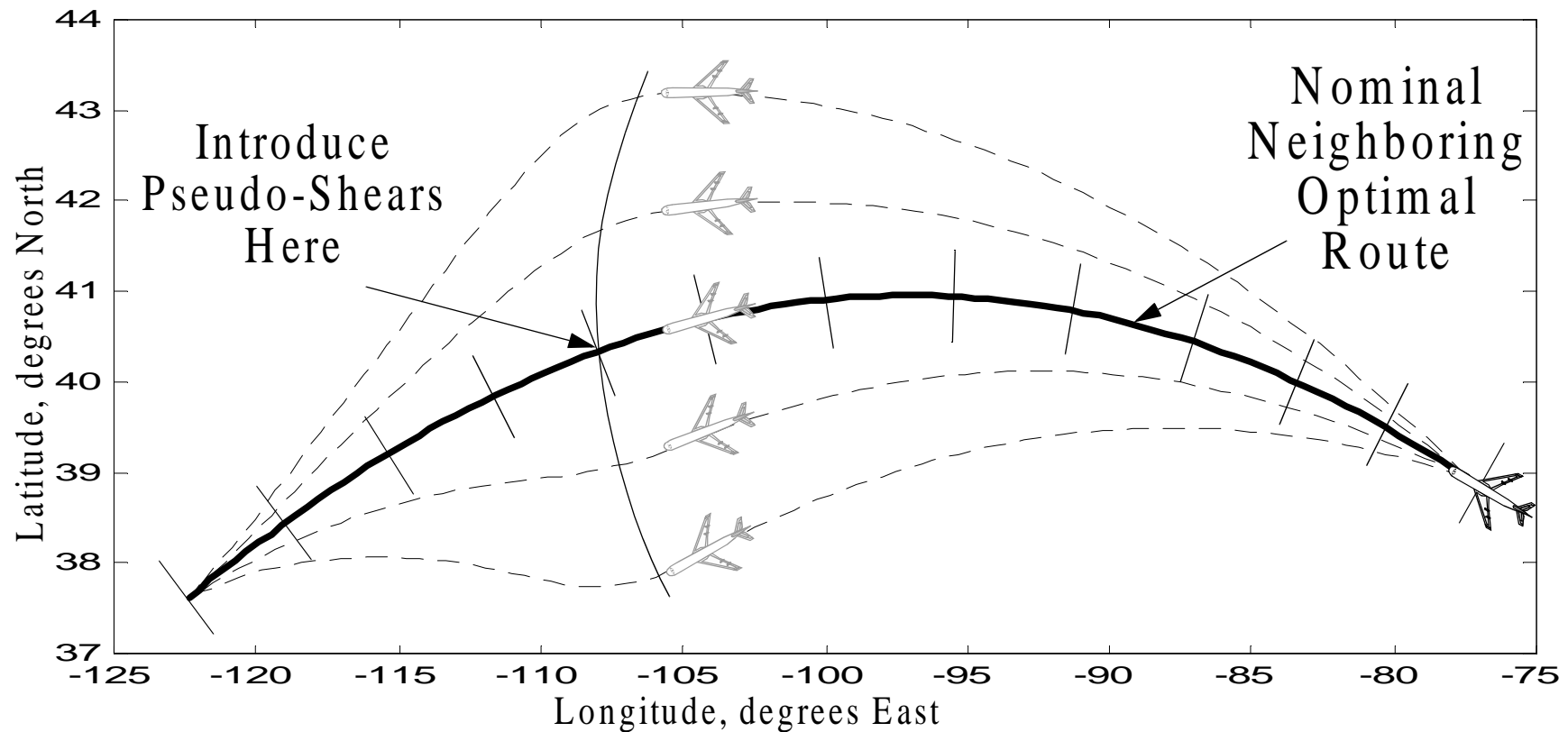
Sequential Optimization
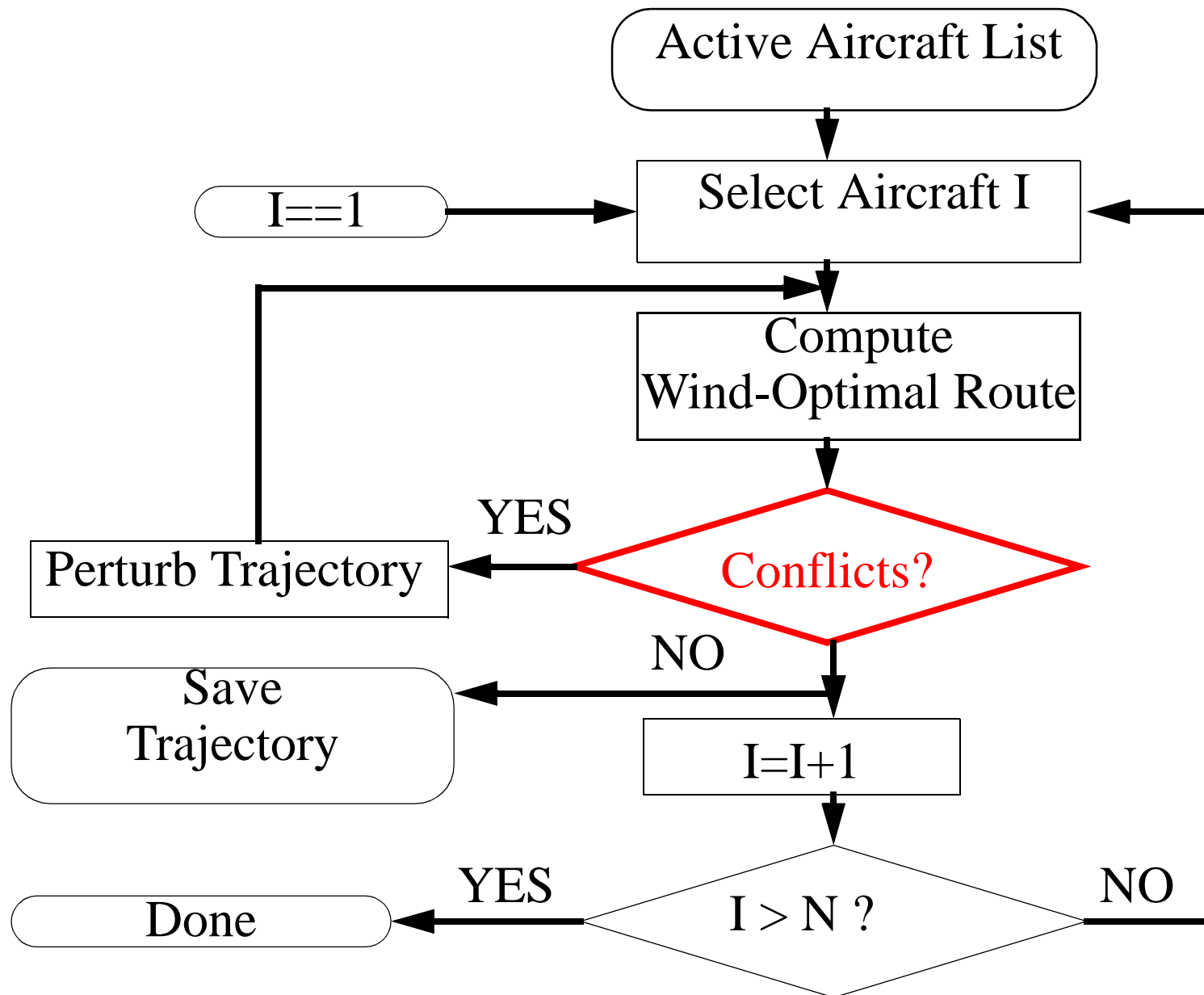
Conflict Grid

- {Lon, Lat, Time} maps to unique grid cell
- Spacing: {5nmi x 5nmi x 30 seconds}
- Up to 7hr "Rolling" time grid
- Memory (for 1 FL): 300 x 500 x 840 bits (16 Mbytes)

- Aircraft in cell? ==> set bit to '1'
- No aircraft in cell? ==> set bit to '0'
- Bad Wx in cell, or SUA? ==> set bit to '1'
- *Virtually free conflict detection!* $O(0)$

Sequential Optimization

Active Aircraft List

↓

Select Aircraft I

I==1 →

↓

Compute
Wind-Optimal Route

↓

Conflicts?

YES → Perturb Trajectory

NO ↓

Save
Trajectory

I=I+1

↓

I > N ?

YES → Done

NO

NOWR Conflict Resolution

- Modify NOWR for Conflict Resolution: Pseudo Wind Shear
- Resulting Conflict-Free Trajectories Near-Wind-Optimal
- Roll the Animation!

Computational Requirements

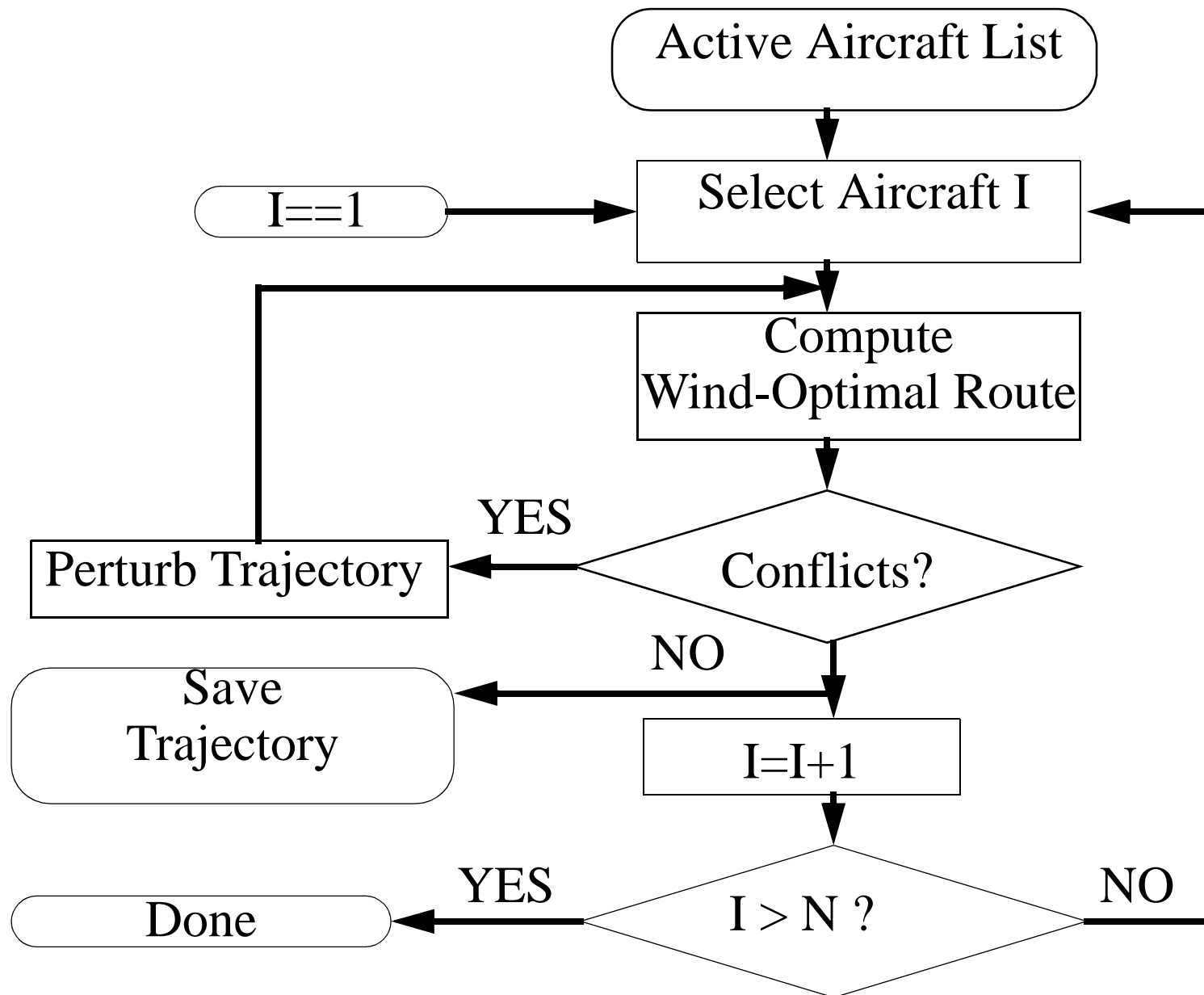**Total Number of Expected Operations for N_{AC} Aircraft:**

$$\sum_{i=1}^{N_{AC}} E[\xi_i] = \left(\sum_{i=1}^{N_{AC}} E[N_{ci}] \right) \cdot [\bar{\chi}_{\text{wind-opt}} + \bar{\chi}_{\text{conf-detect}}]$$

$$N_{ci} \equiv \text{number of conflict resolution iterations for aircraft } i$$
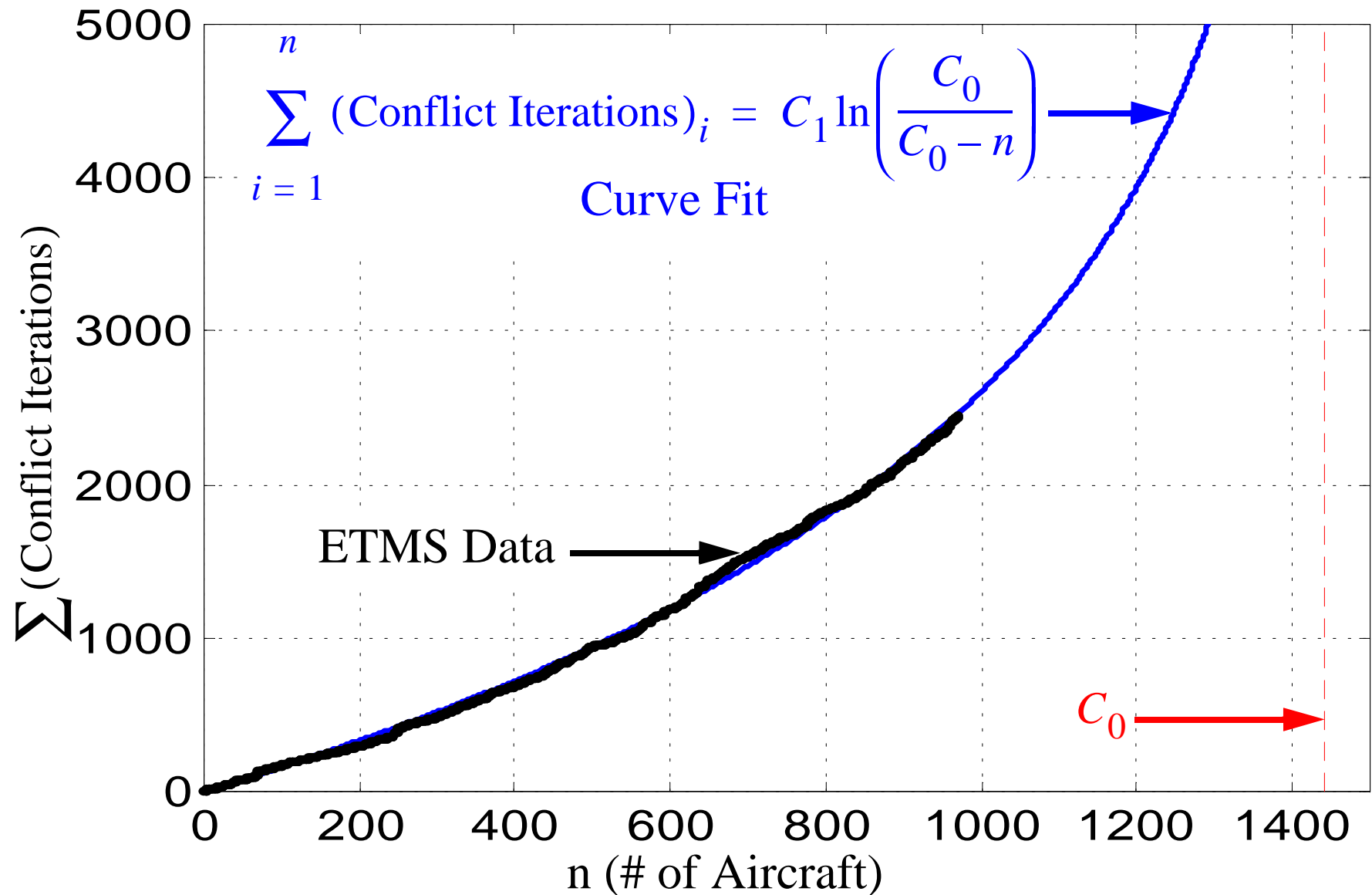
Observations

- $\left(\sum_{i=1}^{N_{AC}} E[N_{ci}] \right) \leq \dfrac{N_{AC}(N_{AC} - 1)}{2}$ (A Polynomial-Time Algorithm)

- Wind-optimal computations are a primitive
- Develop physical model, fit parameters with empirical data

Simulation

Active Aircraft List

Select Aircraft I

I==1

Compute
Wind-Optimal Route

YES

Perturb Trajectory

Conflicts?

NO

Save
Trajectory

I=I+1

YES

Done

I > N ?

NO

Conflict Resolution Model

$$\sum_{i=1}^{n} (\text{Conflict Iterations})_i \;=\; C_1 \ln\!\left(\frac{C_0}{C_0 - n}\right)$$

Curve Fit

ETMS Data

C_0

Simulation Description

- Spherical Earth Model

- Horizontal-Plane

- Initialized with ETMS Data or Simulated Traffic

- Rapid Update Cycle (RUC) Winds

- Modeled Weather Cell & Special-Use Airspace

- Modeled Uncertainty in Aircraft & Wx-Cell Positions
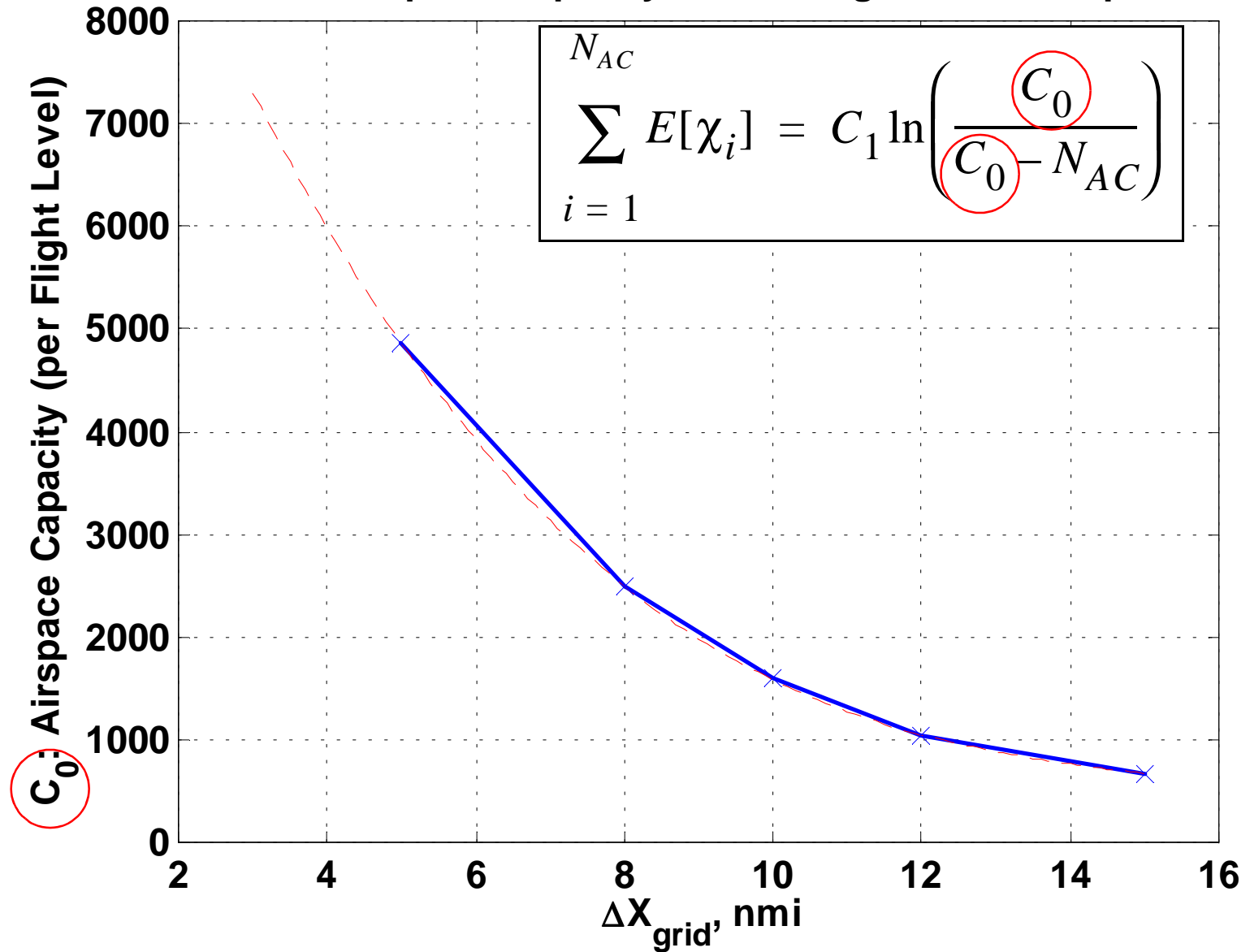
System Simulation Animation

Airspace Capacity Study

- Vary Idealized Sector Loading Constraints
- Use Capacity Model to Measure Predicted Airspace Capacity

Example Sector & Conflict Grid

ΔX_{grid}

ΔX_{grid}
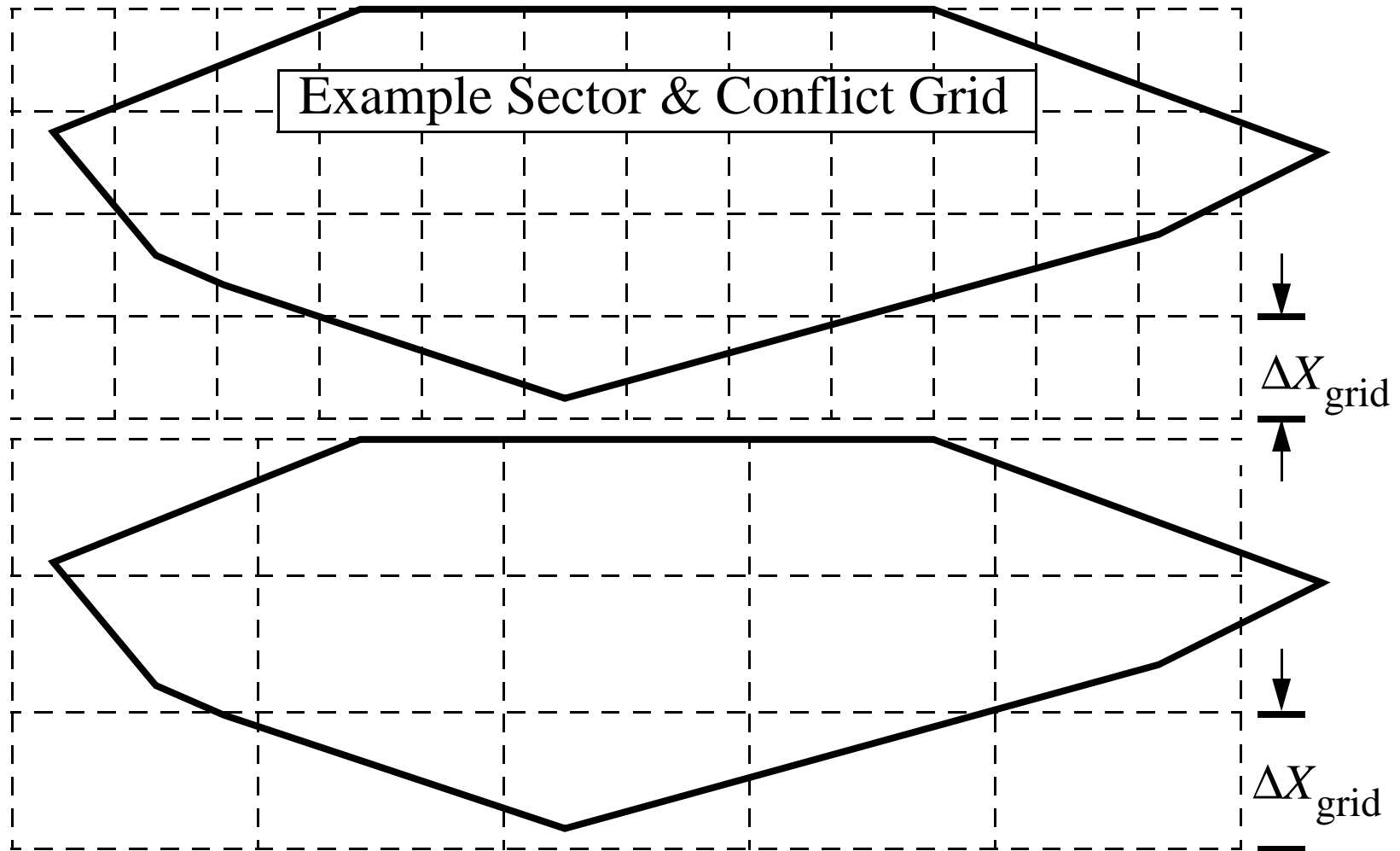
Airspace Capacity

Maximum Airspace Capacity vs. Average Aircraft Separation

$$\sum_{i=1}^{N_{AC}} E[\chi_i] = C_1 \ln\left(\frac{C_0}{C_0 - N_{AC}}\right)$$

Y-axis: C_0: Airspace Capacity (per Flight Level)

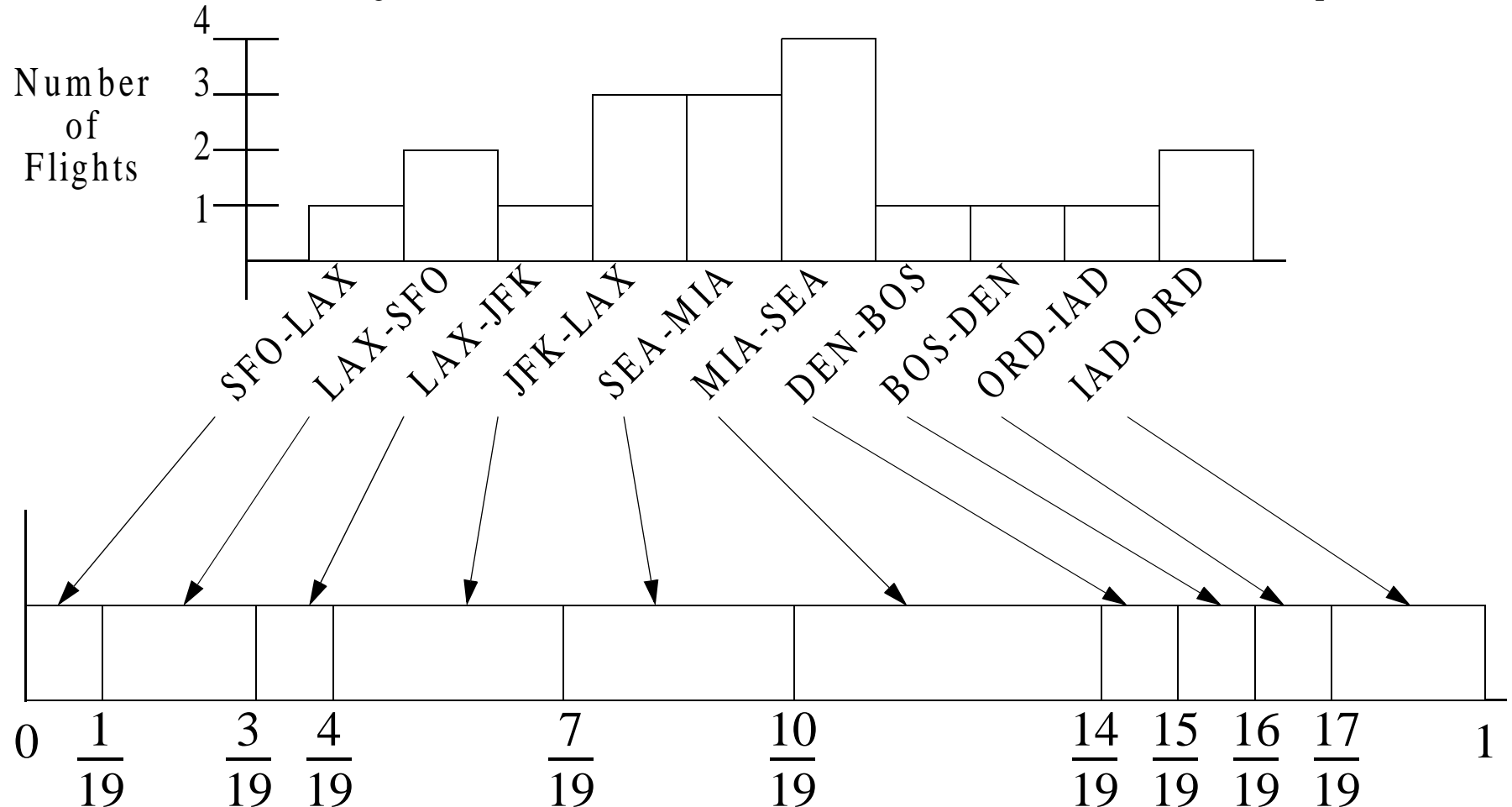X-axis: ΔX_{grid}, nmi

Scenario Development

Realistic Free Flight Scenario Generation

- Begin with Real ETMS Schedule Data

  - Origin Airport

  - Departure Airport

  - Actual Departure Time

- Generate Histogram of # of Aircraft per Route Per Hour

- Create Random Route Generator Based on Histograms

- Utilize Real Wind Data Files

- Utilize Corresponding Weather Data

Scenario Development

Distribution of Origin/Destination Pairs for 1200 UTC -- 1300 UTC (example data)

Roadmap:

2D Algorithm Development in MATLAB Environment

- Perform Basic Computation Timing Analyses
- Examine Effects of Wind Modeling Errors
- Incorporate Weather Cells and Prediction Errors

Port Algorithms to C (or similar) Language

- Software Library Development for VAST & Concept Blending
- Incorporate into FACET for Higher-level Simulations

Extend Algorithms to 3D

- Requires Greater Amount of Memory than 2D
- Requires Compiled Code Speed

Run Higher-Fidelity Simulation and Analyses

- Sector Load Constraints
- Communications Timing Constraints
- Emergency Procedures
- 4D Control Requirements

Conclusion

- Objective is to Achieve Real-Time Conflict-Free Strategic Trajectory Optimization

- Have Developed Basic Algorithms and Demonstrated in 2D

  - Neighboring Optimal Wind Routing (NOWR)
  - Conflict Grid Conflict Detection
  - NOWR Conflict Resolution

- Component Algorithms will be Useful for VAMS

- Will Extend to 3D and to Higher Fidelity

- Will Port to C and to FACET